Single Event Effects (SEE) and Total Ionizing Dose (TID) Test Results for a Step-Down Regulator Controller Evaluated for Use in a Harsh Space Radiation Environment

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***Abstract*—-This paper reports and analyzes recent single event effects (SEE) and total ionizing dose (TID) test results for the Analog Devices RH3845 synchronous current mode step-down controller. This device has been tested and evaluated for use in a harsh space radiation environment.**

I. INTRODUCTION

NASA's Europa Clipper (EC) mission aims to send a radiation tolerant spacecraft into orbit to perform forty-five repeated close science flybys of Jupiter's icy moon, Europa. The goal is to produce high-resolution images of Europa's surface and determine its composition. This will include exploration of signs of a saltwater ocean beneath the icy crust, indicating conditions habitable for life.

One of the key technical challenges for this flight system is the extreme Jovian trapped radiation environment, which is especially harsh at Europa. This severe radiation environment poses a significant risk to mission performance and lifetime [1], and requires electronic parts that must survive very stressing total ionizing dose (TID) and single event effects (SEE) requirement levels. In addition, circuit design mitigation strategies have also been implemented to further reduce risk associated with potential radiation degradation.

This paper reports recent SEE and TID test results from the evaluation of the RH3845 power converter as a potential candidate for use on the Europa Clipper mission. The radiation testing was performed by the Jet Propulsion Laboratory (JPL).

The RH3845 is a high voltage, synchronous, current mode controller, manufactured by Analog Devices Inc. (ADI). It is designed for medium to high power, high efficiency supplies [2]. This part is intended to play a critical role at the heart of the Europa Clipper power subsystem, serving as an interface between the solar array and battery as well as the spacecraft power bus. The adjustable output voltage of the power converter is used to regulate both the spacecraft power bus and limit the battery charge current. The RH3845 is also found in other similar spacecraft power subsystem architectures on many NASA JPL space missions.

The intent of this paper is to summarize the observed functional and parametric failure mechanisms due to radiation degradation in the RH3845, identify root causes, and recommend potential circuit design strategies to mitigate these effects.

II. BACKGROUND AND PURPOSE

Per the ADI datasheet, the RH3845 is a radiation hardened, step-down regulator controller that offers a wide input voltage (V_{IN}) range, from 4V to 60V [2], as well as a programmable output voltage up to 36V. An onboard regulator simplifies the biasing requirements by providing power directly to the integrated circuit (IC) from V_{IN}. The device also features gate drivers capable of driving large N-channel MOSFETs [2]. It is fabricated on a 4µm technology using exclusively bipolar transistors [6].

Prior SEE heavy ion testing from JPL and ADI demonstrated what was believed to be a destructive single event effect mechanism. This event was observed at a linear energy transfer (LET) threshold level less than 30 MeV-cm^2/mg and at applied voltages that do not comply with typical programmatic derating requirements.

This destructive single event effect (D-SEE) was previously explored with the input voltage and switch node (SW) pins tied together, at PV_{IN}=41V or higher [2], [3]. For this case, the supply voltage (V_{CC}) was run off the internal regulator. See Figures 1 and 2 for previous JPL RH3845 SEE test results [3]. The worst case events were observed at normal incidence and room temperature [2], [3]. The destructive SEE LET threshold under these

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conditions was determined to be <20 MeV-cm^2/mg and the saturation cross-section ~7E-5 cm^2/device [3].

The D-SEE failure mechanism was initially attributed to single event burnout (SEB) in the power BJTs as part of the ESD protection circuitry at the input stage [2]. Destructive SEB requires adequate derating on applied voltages in order to mitigate risk. From a design perspective, when the V_{IN} and SW pins are tied together, derating the switch node voltage could pose a potential issue without appropriate isolation (especially when spacecraft bus voltage is a critical design factor to consider).

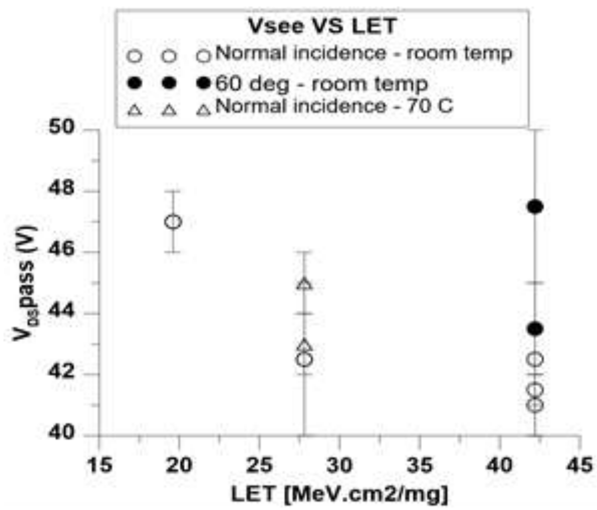

Fig. 1. JPL 2016 data showing applied voltage for onset of D-SEE as a function of LET for various test conditions (V_{IN}=PV_{IN}) [3].

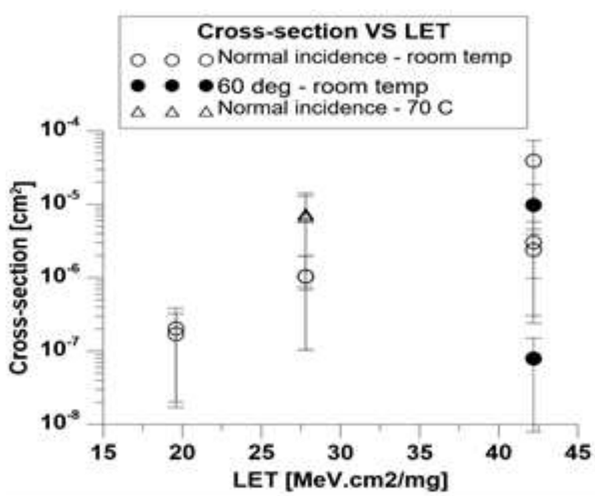

Fig. 2. JPL 2016 cross-section data as a function of LET for various test conditions (V_{IN}=PV_{IN}) [3].

Follow-on testing from Analog Devices, showed that for applications where V_{IN} is independent from PV_{IN}, the switch node voltage can be increased (including derating) while not requiring isolation due to a lower applied input voltage. Under these conditions, destructive failures were observed when PV_{IN} was as high as 49V while V_{IN} is supplied at a voltage of only 15V (connected to V_{CC}).

In order to identify/confirm the destructive SEE failure mechanism and determine root cause, JPL obtained parts from the Europa Clipper flight lot to further investigate the application case where V_{IN} is decoupled from PV_{IN}. The purpose of the additional heavy ion SEE testing was to further determine design margin, define a safe-operating-area (SOA), as well as validate a potential circuit design mitigation approach, where appropriate.

During the course of this destructive SEE testing, an unexpected non-destructive single event functional interrupt (SEFI) mode was discovered, which requires a full power cycle for recovery, unless eliminated.

In addition, a TID Radiation Lot Acceptance Test (RLAT) was performed by JPL at an accelerated low dose rate (42 mRad(Si)/s) out to 300 kRad(Si). The intent of this test was to explore bias dependency of the gamma total dose performance in different modes of operation (i.e. shutdown vs run mode) and verify the TID hardness of the device.

All of the heavy ion and TID test results to date, as well potential design mitigations, are reported and discussed in more detail in Section IV.

III. EXPERIMENTAL PROCEDURE AND TEST FACILITIES

A. Single Event Effects (SEE)

Heavy ion SEE testing was performed by JPL in 2018 and 2019 at the 88-inch cyclotron at Lawrence Berkeley National Laboratory (LBNL) using the 10 MeV/amu and 16 MeV/amu cocktails with various ions and angles to achieve the desired LETs. A cumulative fluence of 1E7 ions/cm^2 was applied, unless a destructive event was observed, in which case the test was stopped.

Laser SEE tests were performed at the JPL Picosecond Single Event Laser Facility in Pasadena, CA. The source is a Sapphire mode-locked Tsunami laser that produces 2.5 ps pulses with a waste size of 1.0 micron (typical energy 1 to 500 pJ per pulse). Automated software is used to control an X-Y stage that can correlate SEE to laser position.

The original intent of the SEE testing was to determine margin when the input and switch node voltages are decoupled to allow for the spacecraft bus voltage operation, while complying with typical project radiation derating requirements (75% on the switch node voltage to mitigate single event burnout). Of course, the applicable derating requirement is also dependent on proper identification of the failure mechanism, which was the primary objective for all subsequent heavy ion tests.

B. *Total Ionizing Dose (TID)*

The expected accumulated total dose level inside the Europa Clipper electronics vault is 150 kRad(Si). Applying a radiation design factor (RDF) of two, it is required that electronic parts are capable of operating up to 300 kRad(Si). At this dose level, standard test methods for RLAT would require one year to complete at a dose rate of 10 mRad(Si)/s (per MIL-STD-883, Test Method 1019, Condition D). This would pose a significant impact to the project schedule. Thus, a risk reduction task was initiated to determine a shorter duration ELDRS test method to address the mission dose profile [4].

Based on the flyby mission trajectory, coupled with the assumed vault shielding configuration, the appropriate dose rate for all Europa Clipper ELDRS testing on bipolar linear devices was determined to be ~45 mRad(Si)/s ± 15%. This value was chosen because it is below the average dose rate at which 90% of the mission dose is received [4].

Therefore, TID irradiation as well as pre- and post-irradiation electrical characterization of the RH3845 was performed at ambient room temperature (25°C) in accordance with MIL-STD-883, Method 1019, Condition C, at the dose rate derived from the mission dose profile. The parts were operated under both biased and unbiased test conditions during irradiation. A step-stress model was implemented and electrical parametric characterization was performed pre-irradiation and after each intermediate dose point out to an accumulated exposure of 300 kRad(Si). All parametric limits and test conditions were derived from the manufacturer datasheet. Irradiation test conditions included implementation of the worst case bias voltage, intended to bound part performance and replicate the flight application. A minimum sample size was identified as five devices per wafer/diffusion lot, per test condition.

All TID irradiations were performed using the low dose rate Cobalt-60 gamma total ionizing dose source on site at the Jet Propulsion Laboratory in Pasadena, CA. The low dose rate source is manufactured by J.L. Sheppard and Associates and is a room irradiator. The cell is calibrated with traceability to NIST standards. The ~45 mRad(Si)/s dose rate was controlled by adjusting the distance between the test articles and the radiation source. Dose rate measurements were performed during the first week of every month of irradiation, and distances were adjusted accordingly to maintain consistent exposure conditions.

IV. TEST RESULTS AND DISCUSSION

A. *Destructive Failure Mechanism*

During heavy ion testing at LBNL in September and November of 2018, what was believed to be a destructive single event effect, was observed at a LET of 38 MeV-cm^2/mg (Yttrium ion, in vacuum, with 2 mil Kapton sheet degrader). The D-SEE occurred when the input and switch node voltages were decoupled, and PV_{IN} was increased to an average onset voltage of 44V. Five devices were characterized and the measured onset voltages for each part are plotted in Figure 3. These results were similar to the failure mechanism observed during prior JPL and ADI testing in 2016.

It is also important to note, for these 2018 beam runs, a 2Ω resistor was added to the SEE test fixtures between the power stage switch node and the IC switch node pin. The intent of this design change was to limit the current at the switch node pin in order to protect the ESD circuitry that was potentially susceptible to the D-SEE. This was the first instance of implementing a circuit design mitigation in order to attempt to eliminate the destructive mechanism.

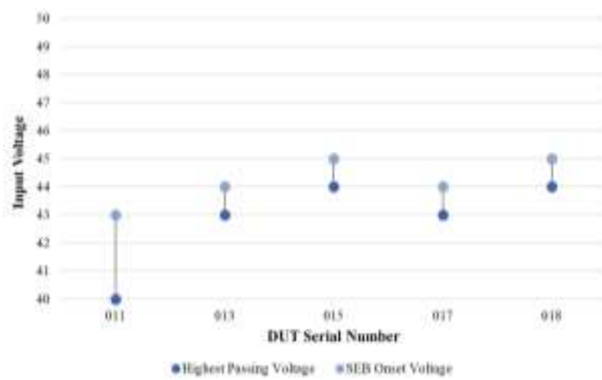

Fig. 3. RH3845 measured destructive SEE onset voltage from LBNL November 2018 test (at LET of 38 MeV-cm^2/mg and temperature of -5°C).

From this test, it was confirmed, the destructive mechanism depends on the applied voltages at V_{IN} and PV_{IN} as reported in [2]. In addition, the following conclusions were drawn with regards to the failure mode: minimal temperature dependence (testing performed at -5°C and room temperature); no switch-node resistor dependence; SOA for D-SEE requires PV_{IN}<45 V (for V_{CC}=V_{IN}=15V). Note, the intent of performing low temperature testing on the flight lot was to determine if the failure mechanism was indeed a single event burnout (SEB) effect, which is worst case cold and can exhibit lot-to-lot variability.

As a result of these observations, a transformer circuit design mitigation was implemented to add isolated gate drivers for the top MOSFETs in the chip. The intent was to decouple the controller input from the switch node voltage while grounding the switch node pin.

Further heavy ion characterization in this circuit configuration was performed in April 2019 in order to continue investigation into understanding the type of failure mechanism. The mitigation was confirmed to be successful, in the sense the RH3845 itself was functioning (the converter was still healthy and switching) after exposure up to a LET of 79 MeV-cm2/mg (Xenon in air at 40°). However, the destructive mechanism still existed for $V_{CC}=V_{IN}=12V$ and $PV_{IN}\geq 50V$ (as opposed to 44V when V_{IN} and PV_{IN} were decoupled – prior to the implementation of the new isolated gate driver transformer circuit). This was our first indication, the destructive mechanism was no longer single event-induced burnout in the power BJTs. However, it should be noted, the destructive effect did not occur for $PV_{IN} < 50V$ up to a cumulative fluence of 1E7 ions/cm2.

Upon completion of this test, we were able to isolate the failure point (and mechanism) to the synchronous MOSFETs that are driving the buck converter. It was determined high voltage transients are potentially causing shoot through in the converter which destroys the FETs via gate activation. For this April 2019 heavy ion test, the FETs used were 150V, 1A rated devices. The gate drive resistance in the current Europa Clipper applications is 2Ω with an output load of 0A. Note, these conditions vary for every use case of this device and are the critical circuit conditions driving root cause of the destructive mechanism.

After observing destruction of the bottom FET on the test circuit, we tuned to a higher in-line gate resistance, from 2Ω to 10Ω. After re-testing at a LET of 79 MeV-cm2/mg, no destructive failures were observed up to PV_{IN} of 100V (fluence of 1E7 ions/cm2) on two different devices.

The RH3845 was then tested again in May 2019, to further investigate the damaging transient-induced overstress. For this test, we added additional probe points on the signal chain to monitor the voltage on the gates. The heavy ion irradiation was performed in air at LBNL using the 16 MeV/amu cocktail with various LETs ranging from 1-75 MeV-cm2/mg.

During the test, anomalous and potentially fault propagating erroneous gate drive signals to the high power processing MOSFETs were observed as indicated by the transient-induced cross-conduction as shown in images shown in Figures 4 and 5. The scope images show both the top and bottom FETs turning on simultaneously. Similar events were recorded under 10 mA and 1A load conditions, which included signatures with multiple pulses and high ringing. Two devices were fully characterized and the Weibull curve is provided in Figure 6. It should be noted, previous SET testing by ADI/Linear Technology did not contain waveforms for the gate drive signals (such as those documented in this paper), although the report did indicate transient events were observed [5], some of which were destructive [6].

Additionally, the destructive failure mechanism was no longer observed during this April 2019 heavy ion test. The boards were redesigned with 24A rated MOSFETs which proved to be more robust to the shoothrough events.

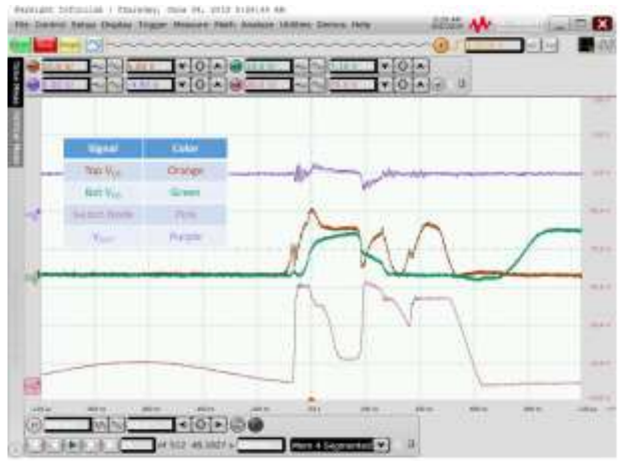

Fig. 4. RH3845 cross-conduction event observed during heavy ion testing – both FETs are turning on simultaneously and multiple pulses were observed ($V_{CC}=V_{IN}=12V$, $PV_{IN}=50V$, $V_{OUT}=5V$ and $I_{LOAD}=10mA$).

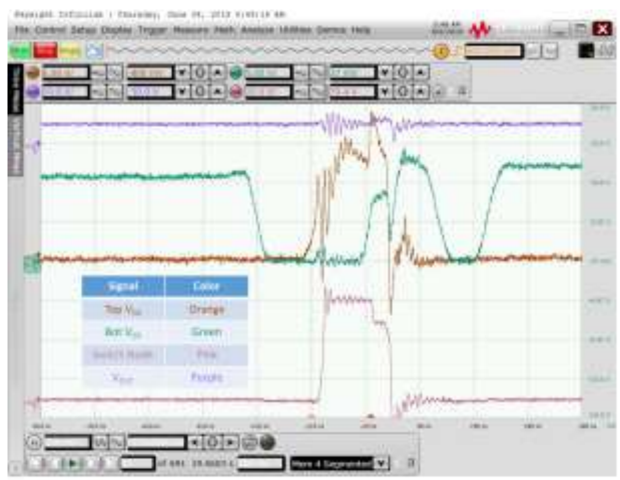

Fig. 5. RH3845 cross-conduction event observed during heavy ion testing – both FETs turning on simultaneously and multiple pulses/high ringing was observed ($V_{CC}=V_{IN}=12V$, $PV_{IN}=50V$, $V_{OUT}=5V$ and $I_{LOAD}=1A$).

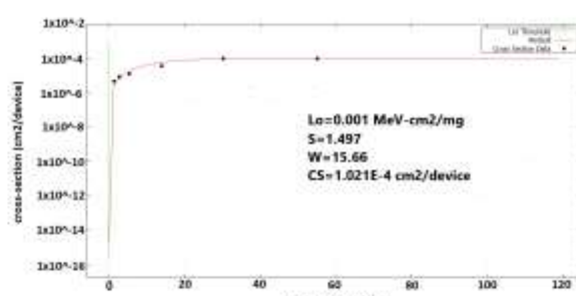

Fig. 6. RH3845 cross-conduction event saturation cross-section plot as a function of LET ($V_{CC}=V_{IN}=12V$, $PV_{IN}=50V$, $V_{OUT}=5V$ and $I_{LOAD}=10mA$).

The heavy ion galactic cosmic ray (GCR) rate (at 1 AU) for the transient-induced gate activation events was calculated to be 0.3 events/device-year. Note, the low LET onset threshold of 0.1 MeV-cm2/mg, indicates the device is potentially proton sensitive.

In summary, electrically it was demonstrated, the cross-conduction effect can be can be found at near random instances during heavy load transitions. This is during turn on, turn off, and transient loading. The root cause of the cross-conduction issue is still under investigation. Since the mechanism is occurring electrically and is not SEE-induced, a potential circuit mitigation to reduce the impact of this effect.

B. Single Event Functional Interrupt (SEFI)

During the heavy ion testing in November 2018, an additional SEFI mode was observed at a LET of 38 MeV-cm2/mg (Yttrium in vacuum with 2 mil Kapton sheet degrader). When this event occurs, the controller switches between Burst and Forced-CCM Mode. As a result, the RH3845 becomes stuck in a linear state during irradiation (when the beam is on). The SEFI event is dependent on V_{CC} and is worst case when V_{CC}=15V (regardless of the input voltage) (with no pre-load applied). The SEFI mode is also induced less frequently under low load conditions < 65 kΩ.

Under these circuit conditions, the switch node stops switching temporarily (in Burst Mode) and remains in that state until recovered. Figure 7 shows the switch node is still active, but the converter is not producing an output voltage and the top gate is not staying on.

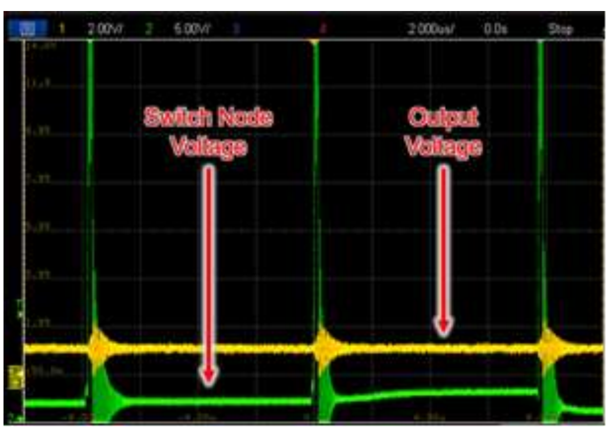

Fig. 7. RH3845 SEFI event (for no load case) was recoverable by stopping the beam or full power cycle of the power supply.

When the SEFI mode fully kicks in, under no load circuit conditions, the switch node falls to ~0V while the output voltage rails to ~8V (5V rail is nominal operation for this low voltage converter). This result is not consistent with the destructive event, which results in no voltage on the chip.

The heavy ion tests confirmed, the SEFI mechanism occurs regardless of applied voltage, is highly dependent on load conditions, and is recoverable by stopping the beam or full power cycle of the power supply.

The suspected root-case area is the mode-selection portion of the RH3845 die, resulting in a temporary state flip. The SEE laser test in the JPL lab also confirmed the transient effect does not cause permanent damage to the die as long as PV_{IN} < 45V.

Follow-on heavy ion testing was performed in April 2019 to confirm a design mitigation approach. The effect was successfully mitigated by pre-loading the converter above 1 mA (we tested at 10 mA) to avoid the linear state and maintain the output voltage. The design was proven to be stable in both the Burst Mode and CCM operation. A total of five different RH3845 devices were tested with V_{CC}=V_{IN}=15V and PV_{IN}=20V, at an LET of 79 MeV-cm2/mg (Xenon beam in air at 45 degrees using 16 MeV/amu cocktail at LBNL), to a cumulative fluence of 1E7 ions/cm2. The applied voltage was chosen as to not induce the destructive mechanism. No events were recorded with the pre-load circuit mitigation in place.

C. Low Dose Rate TID RLAT

Finally, TID radiation lot acceptance testing was completed at a low dose rate of 42 mRad(Si)/s out to 300 kRad(Si) on the RH3845 flight lot. Five devices were tested unbiased, an additional five parts were biased during irradiation in run mode, and five were biased in shutdown mode per the manufacturer generic bias circuits (V1=5V, +V2=40V, R_T = 49.9kΩ). The parametric tests were performed at 3.3V for a frequency of 150 kHz.

Although a few parametric non-conformances were noted, primarily the bias supply current which fell slightly out of spec starting at 250 kRad(Si), all devices were functional post 300 kRad(Si). The data also indicated no bias dependency in the response. Figures 8-10 show the response of critical parameters as a function of TID. The mean value of the five samples tested, for each operating condition, has been plotted. As shown in Figure 8, the reference voltage did degrade as a function of dose, however it still remained in spec (per the ADI RH3845 datasheet limits) post 300 kRad(Si).

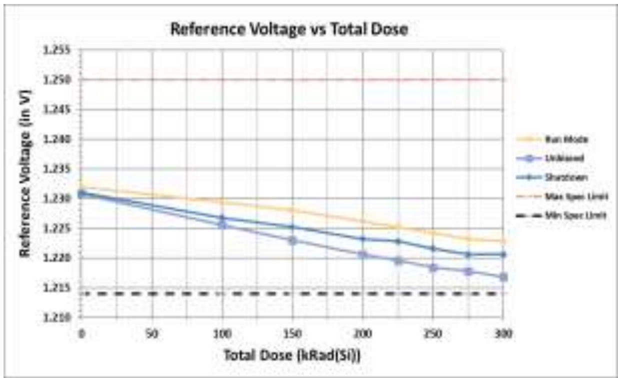

Fig. 8. Mean reference voltage as a function of TID out to 300 kRad(Si) at low dose rate of 42 mRad(Si)/s. All test devices remained within the manufacturer spec limits post 300 kRad(Si) for all modes of operation.

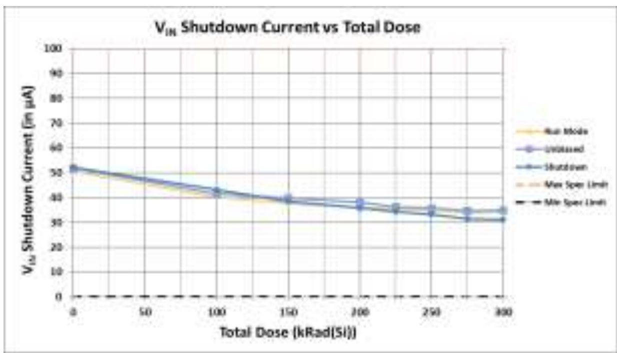

Fig. 9. Mean shutdown current as a function of TID out to 300 kRad(Si) at low dose rate of 42 mRad(Si)/s. All test devices remained within the manufacturer spec limits post 300 kRad(Si) for all modes of operation.

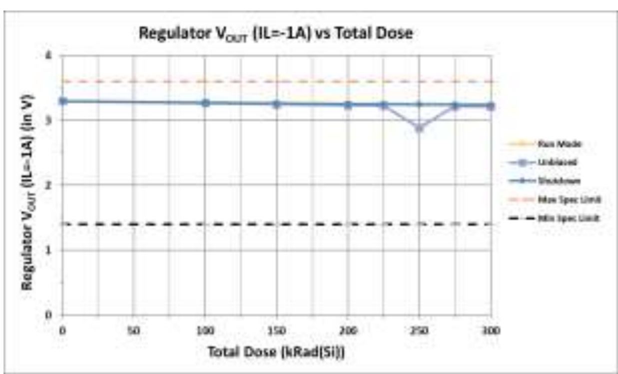

Fig. 10. Mean regulator output voltage as a function of TID out to 300 kRad(Si) at low dose rate of 42 mRad(Si)/s. All test devices remained within the manufacturer spec limits post 300 kRad(Si) for all modes of operation.

V. Conclusion

In conclusion, the SEE and TID investigation of the RH3845 PWM controller from Analog Devices is summarized herein. Ultimately, the main goal of the SEE testing was to identify the destructive failure mechanism, map out a safe-operating-area, and implement circuit design mitigations to eliminate the effect. All of the testing to date has proved successful in uncovering and understanding the failure mechanism.

It has been concluded the destructive effect is actually not attributed to single event burnout in the ESD circuitry after all. Instead, the mechanism is being induced electrically, internal to the part, resulting in cross-conduction in the chip, which was uncovered during the heavy ion testing. The SEE characterization showed the isolated gate driver transformer circuit mitigation proved to protect the RH3845 controller itself, from being destroyed; however, it did not prevent both the top and bottom MOSFETs from turning on simultaneously. A final circuit fix for the cross-conduction issue is still being explored. However, it must be understood, the cross-conduction issue is dependent on the applied voltage on the chip, the gate resistance, and the rating of the FETs used in the circuit design.

Follow-on electrical and heavy ion testing will be performed to formally bound the worst case conditions for inducing the destructive effect and prove the cross-conduction issue has been eliminated. It should also be noted, the SEFI linear mode was also successfully mitigated using the 1 mA pre-load.

Finally, the TID RLAT at low dose rate verified the device is indeed radiation hardened and robust to 300 kRad(Si). A few very minor parametric non-conformances were noted, however, all devices were fully functional post 300 kRad(Si).

VI. References

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